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Indian Standard

SHORT-CIRCUIT CURRENT EVALUATION WITH SPECIAL REGARD TO RATED SHORT-CIRCUIT CAPACITY OF CIRCUIT-BREAKERS IN INSTALLATIONS IN SHIPS — GUIDE

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Electrical Equipment and Installations in Ships Sectional Committee, ET 26

NATIONAL FOREWORD

This Indian Standard is identical with IEC 363 (1972) 'Short-circuit current evaluation with special regard to rated short-circuit capacity of circuit-breakers in installations in ships'.

The text of the IEC standard has been considered and approved by ET 26 Electrical Equipment and Installations in Ships Sectional Committee of BIS as suitable for publication as Indian Standard.

In this Indian Standard the following International Standard is referred to. Read in its place, the following:

International Standard	*Indian Standard*
IEC 157-1	IS 13947 (Part 2) : 1993

Certain conventions appearing in this dual number standard are not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.

b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

c) Only the English language text in the IEC standard has been retained while adopting it in this Indian Standard.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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Indian Standard

SHORT-CIRCUIT CURRENT EVALUATION WITH SPECIAL REGARD TO RATED SHORT-CIRCUIT CAPACITY OF CIRCUIT-BREAKERS IN INSTALLATIONS IN SHIPS — GUIDE

SECTION ONE — A.C. SYSTEMS

The aim of this section is to point out the essential differences between the circuit conditions assumed as a basis for the short-circuit rating of circuit-breakers according to IEC Publication 157-1, Low-voltage distribution switchgear, Part 1 : Circuit-breakers, and those peculiar to electrical systems in ships.

Calculations of short-circuit currents should be made at each point in the system where protective devices are fitted.

1. Evaluation of the maximum short-circuit current and of the corresponding power factor in a system

For the evaluation of the maximum short-circuit current in a system, i.e., in case of fault occurring in close proximity to the main busbars, the short-circuit impedance can be assumed generally to coincide with the reactance of the rotating machinery connected in the system, the resistance being regarded as negligible.

For evaluating the short-circuit power factor it is necessary, on the contrary, to take into account the resistance of the circuit affected by the fault, i.e., the resistance of the machinery as well as of any circuit element (connections, switchgear, etc.), in series.

Note. — Attention is drawn to the fact that the reactance and resistance of the circuit-breaker to be installed in a given point shall not be considered, according to the definition of prospective short-circuit current of a circuit (with respect to a switching device situated therein).

The reactances of rotating machinery cannot be regarded as constant during the short-circuit.

2. Short-circuit current of generators (limited to the first few cycles)

The root mean square (r.m.s.) value of the a.c. component of the short-circuit current of a generator, extrapolated at time zero (instant of initiation) by the envelope of the current waves, is indicated as sub-transient short-circuit current I''. (See Figure 1, page 9.)

When the short-circuit occurs on the generator off-load at rated voltage V_N, the sub-transient short-circuit current $I''_{\text{no load}}$ is given by the equation :

$$I''_{\text{no load}} = \frac{V_N}{X''_d} = \left(\frac{1}{x''_d}\right) I_N \qquad (1)$$

where :

X''_d = the direct axis sub-transient reactance of the generator,
x''_d = the same reactance expressed in percent,
I_N = the rated current of the generator.

When the short-circuit occurs on the generator at rated load, i.e., at rated voltage with rated current and rated power factor, the sub-transient short-circuit current $I''_{\text{rated load}}$ can be obtained from the above sub-transient short-circuit current $I''_{\text{no load}}$ by an appropriate multiplying factor based on the characteristics of the machine. When precise information is lacking, this multiplying factor can be chosen at a value of 1.1 (see also Clause 5).

The r.m.s. value of the a.c. component of the short-circuit current of a generator decreases at a rate, which becomes less after the first cycles of current, this time interval corresponding to the sub-transient phenomenon. (See Figure 1, page 9.)

The r.m.s. value of the a.c. component of the current, after the sub-transient phenomenon is extinguished, but extrapolated to time zero (see Figure 1), is indicated as transient short-circuit current I'.

When the short-circuit occurs on the generator off-load at rated voltage V_N, the transient short-circuit current $I'_{\text{no load}}$ is given by the equation :

$$I'_{\text{no load}} = \frac{V_N}{X'_d} = \left(\frac{1}{x'_d}\right) I_N \qquad (2)$$

where :

X'_d = the direct axis transient reactance of the generator
x'_d = the same reactance expressed in per cent
I_N = the rated current of the generator

When the short-circuit occurs on the generator at rated load, i.e., at rated voltage with rated current and rated power factor, the transient short-circuit current $I'_{\text{rated load}}$ can be obtained from the above transient short-circuit current $I'_{\text{no load}}$ by an appropriate multiplying factor, as for the sub-transient short-circuit current. When precise information is lacking, this multiplying factor can be chosen at a value of 1.1 (see also Clause 5).

The time constant of the exponential decrease of the amplitude of the a.c. component of the short-circuit current, during the sub-transient phenomenon, is the sub-transient time constant T''_d (see Figure 1); the time constant of the transient phenomenon is the transient time constant T'_d.

The first of these time constants T''_d, is of prime interest in considering the short-circuit currents in the systems related to the short-circuit rating of the circuit-breakers to be installed therein.

The r.m.s. value during the first few cycles can be obtained from :

$$I_{ac} = (I'' - I')\,\varepsilon^{-t/T''_d} + I' \qquad (3)$$

without appreciable error.

3. Maximum possible peak value of the short-circuit current of generators

The maximum possible peak value of the current corresponds to the presence of the maximum possible d.c. component for a given a.c. component. The maximum possible peak value $I_{\text{peak max}}$ of the short-circuit current (instantaneous value) is related to the sub-transient current I'' (r.m.s. value of the a.c. component extrapolated at time zero). It also depends upon the ratio x'_d/x''_d and upon the sub-transient time constant T''_d, which determine the decrease of the a.c. component during the time interval required by the asymmetrical short-circuit current to reach its maximum peak value, and moreover, upon the short-circuit power factor, which determines the decrease of the d.c. component during the same time interval with the time constant T_{dc}.

The maximum possible peak value can be calculated with the same formula given for the r.m.s. value taking into account that the r.m.s. value stated for I_{ac} must be multiplied by $\sqrt{2}$ whereas the d.c. component extrapolated at time zero has a value of $I''\sqrt{2}$.

The following formula may be used for determining the maximum peak value which is assumed to occur at time $t = \frac{1}{2} T$, T being the time of one cycle.

$$I_{\text{peak max}} = \sqrt{2}\,[(I''-I')\,\varepsilon^{-T/2T''_d} + I'] + \sqrt{2}\,I''\,\varepsilon^{-T/2T_{dc}} \qquad (4)$$

Instead of calculating I_{peak} with this formula, diagrams may be used. Figures 2, 3 and 4 (pages 11 and 12) show, as functions of the ratio x'_d/x''_d, the multiplying factors by which $I_{\text{peak max}}$ can be obtained from I'', for different values of T''_d and for different values of the short-circuit power factor. These diagrams are referred to conditions of no load for the generator before the occurrence of the short-circuit, i.e., to the current $I''_{\text{no load}}$ (see Clause 5). The Figures 2a, 3a and 4a (page 11) are for a frequency of 50 Hz; the figures 2b, 3b and 4b (page 12) are for 60 Hz.

4. Short-circuit current of motors

As the reactances of motors connected in the system are significant in determining the short-circuit equivalent impedance, the contribution of these motors to the actual short-circuit current should be evaluated in the same way as for generators.

4.1 For induction motors, account should be taken of the fact that:

a) There is no sustained short-circuit current supplied by the motors, because of the extinction of the short-circuit current at the end of the transient phenomenon.

b) The internal voltage of the motors, i.e., the voltage supplying the current contribution of the motors at the short-circuit fault, is less than the line voltage (rated voltage of the system) and it has the lowest value when the motors are running at rated load (overload not being considered as normal service condition).

4.2 When more precise information is lacking, it can be assumed as a first approximation that the contribution of motors is that of one motor only, directly connected to main busbars, with a rated power equal to the sum of rated powers of all the motors which may be running simultaneously in service.

4.2.1 The r.m.s. value of the a.c. component I''_M of the short-circuit current arising from this motor (running at rated voltage and no load) extrapolated at time zero (initiation of the short-circuit), is:

$$I''_M = 6.25\,I_N \qquad (5a)$$

where:

I_N = the rated current of this motor
Conditions of load different from zero lead to lower values for I''_M.

4.2.2 The decrease of the a.c. component I''_M of the short-circuit current due to this motor is such as to correspond to the following r.m.s. values as a function of time:

Time (in cycles) after the instant of short-circuit initiation	A.C. component of the short-circuit current $I_{M(t)}$	
1	$I_{M\,(T)} = 2.5\,I_N$	(5b)
2	$I_{M\,(2T)} = I_N$	(5c)

4.2.3 The power factor of the short-circuit current I_M due to induction motors, i.e., the cosine of the angle between the internal voltage and the short-circuit current, is not less than 0.3. The maximum possible peak value of this short-circuit current cannot therefore exceed the value :

$$I_{M\ \text{peak max}} = 8\ I_N \tag{6}$$

For large motors, the above approximation may not be adequate and precise calculation may be necessary using the following information :

P_n = rated power, in kVA
Z_b = impedance of the motor with rotor locked (z_b in per cent)
X_b = reactance of the motor with rotor locked (x_b in per cent)
R_r = rotor resistance (r_r in per cent)
R_s = stator resistance (r_s in per cent)

$$\text{transient time constant, in seconds: } T' = \frac{x_b}{2\ \pi\ fr_r} \tag{7}$$

$$\text{time constant of the d.c. component: } T_{dc} = \frac{x_b}{2\ \pi\ fr_s} \tag{8}$$

The short-circuit current at the terminals of a motor is expressed by the formulae :

$$\text{A.C. component: } I_{ac} = \frac{V_N}{Z_b}\ \varepsilon^{-t/T'} \tag{9}$$

$$\text{D.C. component: } I_{dc} = \sqrt{2}\ \frac{V_N}{Z_b}\ \varepsilon^{-t/T_{dc}} \tag{10}$$

While the peak current at time $t = \frac{1}{2}\ T$ is obtained by the formula :

$$I_{pr} = \sqrt{2}\ \frac{V_N}{Z_b}\ \varepsilon^{-T/2\ T'} + \sqrt{2}\ \frac{V_N}{Z_b}\ \varepsilon^{-T/2\ T_{dc}} \tag{11}$$

5. Evaluation of the maximum possible peak value of the short-circuit current in case of fault near the main busbars

The maximum possible peak value of the short-circuit current is generally obtained by combining the contributions of generators and motors connected in the system, assuming that impedances in series, other than those inherent in the machines, are negligible.

For the maximum possible peak value, it is not required to apply the multiplying factor as under Clause 2.

It can be generally accepted to refer to generators off load and to evaluate the maximum resulting peak value by the arithmetical sum of the peak values separately evaluated for the generator(s) (see Clause 3) and for the motors (see Clause 4).

This is justified by considering that, although the short-circuit current of a generator increases with loading under normal conditions (power factor lagging) in consequence of the increased internal voltage, on the other hand, the peak value of the total short-circuit current (maximum possible) does not increase by the same ratio of the a.c. component of the short-circuit current, but less. This effect depends on the fact that the conditions of the d.c. component are different. Moreover, the contribution of motors is reduced when motors are on load.

6. Evaluation of the short-circuit current in case of fault remote from the main busbars

When the point of fault is remote from the main switchboard, all external impedances between the main switchboard and the point of fault are to be taken into account.

The effect of such impedances on the short-circuit current arising from generators corresponds to the formulae:

sub-transient impedance: $$\begin{aligned} Z''_e &= (R_s + R_e) + j\,(X''_d + X_e) \\ z''_e &= (r_s + r_e) + j\,(x''_d + x_e) \end{aligned} \quad \text{in per cent} \tag{12}$$

transient impedance: $$\begin{aligned} Z'_e &= (R_s + R_e) + j\,(X'_d + X_e) \\ z'_e &= (r_s + r_e) + j\,(x'_d + x_e) \end{aligned} \quad \text{in per cent} \tag{13}$$

Z''_e resp. Z'_e = external impedances (z'_e resp. z''_e in per cent) during the first cycles.

where:

R_s = stator resistance (r_s in per cent),
R_e = external resistance; cables, busbars, etc. (r_e in per cent),
X_e = external reactance (x_e in per cent)

and as regards the time constants:

sub-transient time constant, in seconds: $$T''_e = T''_d \left[\frac{1 + (x_e/x'')}{1 + (x_e/x')}\right] \tag{14}$$

time constant of the d.c. component, in seconds: $$T_{e_{dc}} = \frac{T_{dc} + (x_e/2\,\pi f R_s)}{1 + (R_e/R_s)} \tag{15}$$

Due to the fact that only the first few cycles are considered in this Report, the variation according to the transient time constant may be neglected.

Corresponding formulae are used for motors. In general, it is not necessary to take into account the contribution of motors remote from the point of fault.

The values of short-circuit current can be obtained in the same way as given in Clauses 2 and 3 from:

$$I_{ac} = (I''_e - I'_e)\,\varepsilon^{-t/T''_e} + I'_e \tag{16}$$

$$I_{\text{peak max}} = \sqrt{2}\,\left[(I''_e - I'_e)\,\varepsilon^{-T/2\,T''_e} + I'_e\right] + \sqrt{2}\,I''_e\,\varepsilon^{-T/2\,T_{e_{dc}}} \tag{17}$$

where:

$$I''_e = V_N/Z''_e \tag{18}$$

$$I'_e = V_N/Z'_e \tag{19}$$

7. Choice of circuit-breakers of short-circuit rating conforming to IEC Publication 157-1, for application in electrical systems on ships

The evaluation of the maximum possible peak value of the prospective short-circuit current at the point of application of a circuit-breaker identifies the rated short-circuit making capacity required for the circuit-breaker itself.

The correlated rated short-circuit breaking capacity (if the rating conforms to IEC Publication 157-1) can be obtained by applying the following Table I where the relationship between rated short-circuit breaking and making capacity is given (Table I is taken from Table I, Sub-clause 4.3.4 of IEC Publication 157-1).

TABLE I

Rated short-circuit breaking capacity A	Multiplying factor for obtaining rated short-circuit making capacity
≤10 000	1.7
10 001-20 000	2.0
20 001-50 000	2.1
> 50 000	2.2

The relationship between rated short-circuit breaking capacity and rated short-circuit making capacity is based:

- on the figures specified below for the short-circuit power factor;
- on the assumption that the a.c. component of the short-circuit current maintains constant its r.m.s. value during the short-circuit.

As a consequence of this assumption, the rated breaking capacity of a circuit-breaker chosen on the basis of the required making capacity at the point of its actual installation will, therefore, be adequate; or in excess, if the a.c. component of the actual short-circuit current is affected by a decrement different from zero, provided that the power factor of the short-circuit rating of the circuit-breaker does not exceed the short-circuit power factor evaluated for the point of actual application.

Attention is drawn to the fact that the short-circuit rating according to IEC Publication 157-1 is based on values of short-circuit power factors not less than the limits specified in Table II (from Table VII, Sub-clause 8.2.4.5 of IEC Publication 157-1).

TABLE II

Rated short-circuit breaking capacity A	Short-circuit power factor not less than
≤ 10 000	0.5
10 001-20 000	0.3
20 001-50 000	0.25
> 50 000	0.2

In cases where the short-circuit power factor evaluated for a system is substantially less than that assumed in the short-circuit rating of a circuit-breaker conforming to IEC Publication 157-1, the manufacturer shall be asked to declare the rating he will assign to his circuit-breaker with a short-circuit power factor sufficiently less than that of IEC Publication 157-1.

In many practical cases, the manufacturer may be asked to produce only a test report of his circuit-breaker tested with the required short-circuit power factor less than that prescribed in IEC Publication 157-1, and with unaltered making capacity.

The prospective current of such a test shall be obtained from the value of the making capacity by the multiplying factor corresponding to the required short-circuit power factor.

The following Table III gives the multiplying factors as functions of the short-circuit power factors.

TABLE III

Short-circuit power factors (less than those of IEC Publication 157-1)	Multiplying factors (for obtaining the correlated breaking capacity from the required making capacity, under the assumption of a.c. component constant)
0.15	1/2.30
0.10	1/2.45
0.05	1/2.62

This prospective current identifies the new breaking capacity to be assigned to the circuit-breaker with the new required short-circuit power factor. This same prospective current shall have its a.c. component without any decrement, according to the basic assumptions of IEC Publication 157-1.

In particular cases, special tests may be justified allowing a decrement of the a.c. component of the test current with the new required short-circuit power factor, provided that:

- the decrement to be expected for the a.c. component of the short-circuit current in the relevant application is known;
- the decrement affecting the a.c. component of the test current does not exceed that of the relevant application.

Circuit-breakers with short-circuit rating conforming to the above criteria, are suitable for application in marine systems, their inherent breaking capacity being adequate to the actual application, or in excess.

For example, if the maximum peak value of the prospective short-circuit current evaluated in the point of application of a circuit-breaker, for a particular case, is about 40 kA, and the power factor of the evaluated short-circuit current is about 0.25, a circuit-breaker with rated short-circuit breaking capacity (according to IEC Publication 157-1) of 40(1/2.0) = 20 kA (see Table I) will be suitable for the relevant application, since the short-circuit power factor corresponding to the rated breaking capacity (see Table II) does not exceed the short-circuit power factor evaluated for the application itself.

On the contrary, if the maximum peak value of the prospective short-circuit current evaluated for a particular application is again 40 kA, but the short-circuit power factor results in a value less than 0.25, e.g., about 0.10, a circuit-breaker rated according to IEC Publication 157-1 may not be suitable for this application. Such a circuit-breaker, having rated making capacity not less than 40 kA, should be tested according to the test procedure of IEC Publication 157-1 but with a short-circuit power factor not exceeding the value of 0.10, required by the relevant application, and with a prospective current of 40(1/2.45) = 16.4 kA at least (see Table III). If the circuit-breaker passes this test, it is suitable for the relevant application.

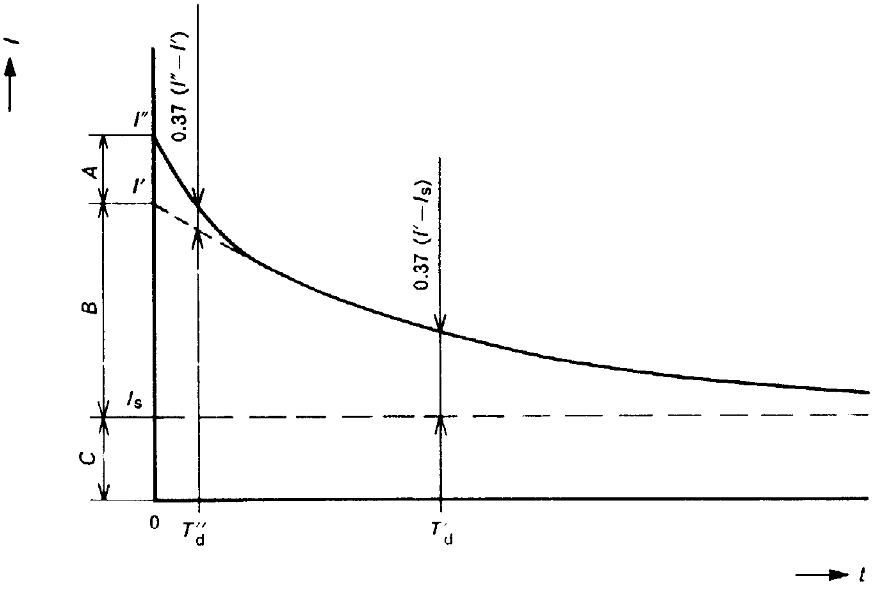


FIG. 1. — Envelope of the r.m.s. value of the current waves of a short-circuit corresponding to the first cycles.

Note. — After the first few cycles, the value of the short-circuit current as well as the steady-state value depend on the regulation and excitation systems.

The envelope of the short-circuit current (r.m.s.) in Figure 1, page 9, can be expressed by:

$$I'' = A + B + C$$

taking into account that:

$A = (I'' - I')\,\varepsilon^{-t/T''_{\mathrm{d}}}$, $\quad I'' = \dfrac{V_{\mathrm{N}}}{X''_{\mathrm{d}}}$, $\quad I' = \dfrac{V_{\mathrm{N}}}{X'_{\mathrm{d}}}$,

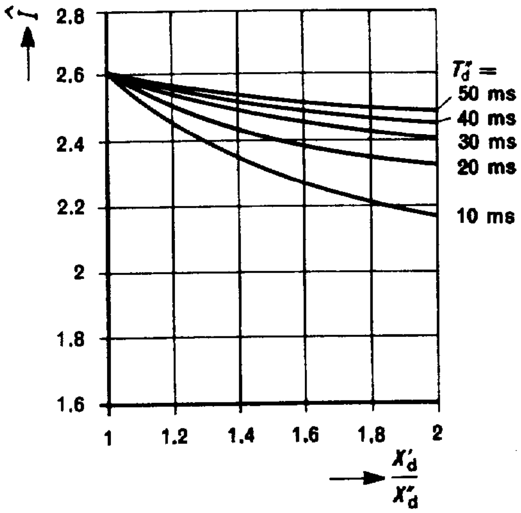
$B = (I' - I_{\mathrm{s}})\,\varepsilon^{-t/T'_{\mathrm{d}}}$

$C = I_{\mathrm{s}}$

so that I_{ac} in r.m.s. value:

$$I_{\mathrm{ac}} = (I'' - I')\,\varepsilon^{-t/T''_{\mathrm{d}}} + (I' - I_{\mathrm{s}})\,\varepsilon^{-t/T'_{\mathrm{d}}} + I_{\mathrm{s}}\ \text{(r.m.s.)} \tag{20}$$

Factors for $I_{\text{peak max}}$ for times T''_d for 50 Hz
Multiplying factor $= f(x'_d)/x''_d$ for 50 Hz and different T''_d



$\hat{I}$ = multiplying factor $= \frac{I_{\text{peak max}}}{I''_{\text{no load}}}$

FIG. 2a. — Cos $\varphi = 0.05$.

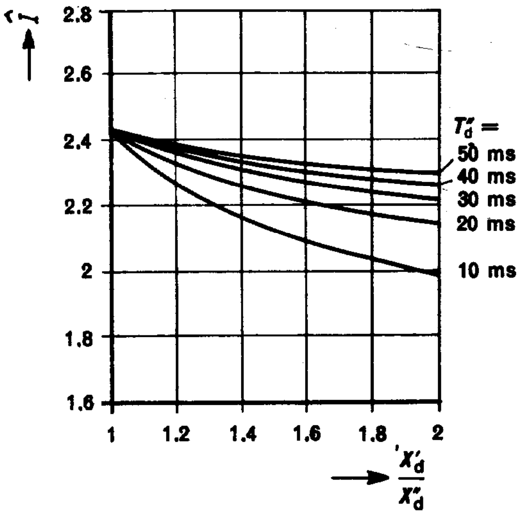


FIG. 3a. — Cos $\varphi = 0.1$.

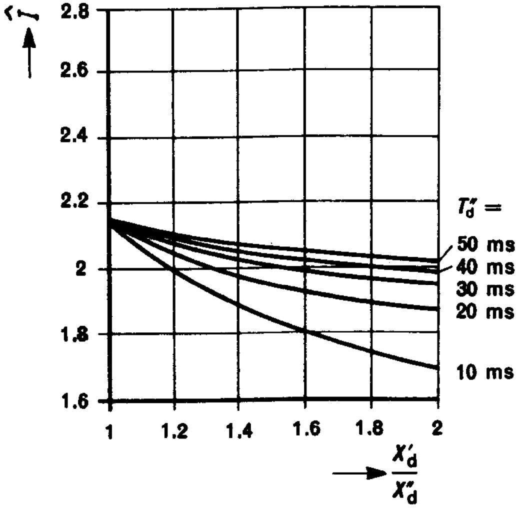
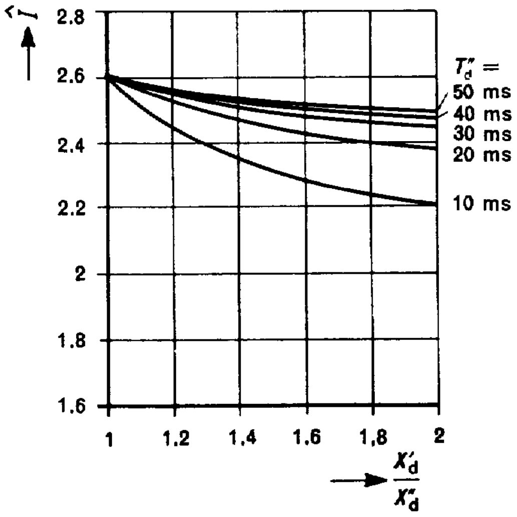


FIG. 4a. — Cos $\varphi = 0.2$.

Factors for $I_{\text{peak max}}$ for times T''_{d} for 60 Hz

Multiplying factor $= f(x'_{\text{d}}/x''_{\text{d}})$ for 60 Hz and different T''_{d}



$$\hat{I} = \text{multiplying factor} = \frac{I_{\text{peak max}}}{I''_{\text{no load}}}$$

FIG. 2b. — Cos φ = 0.05.

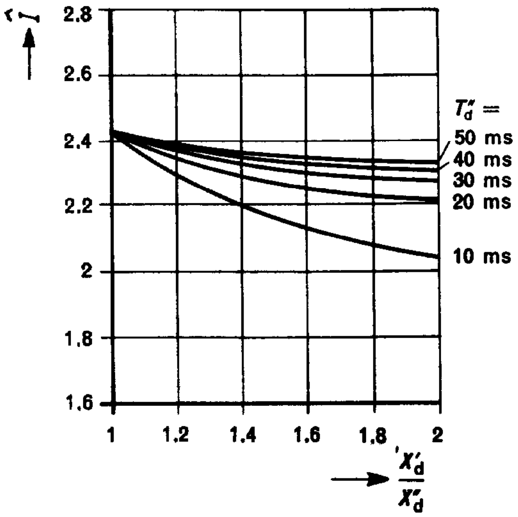


FIG. 3b. — Cos φ = 0.1.

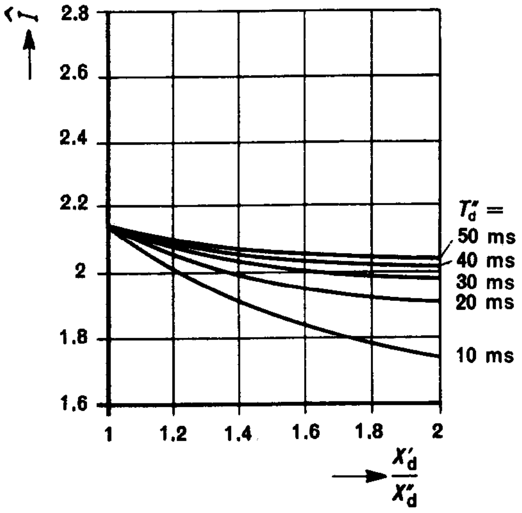


FIG. 4b. — Cos φ = 0.2.

8. Example of a short-circuit calculation

8.1 *General*

This example is hypothetical and does not represent any existing plant. It serves only to explain how to calculate and to estimate. The calculated parameters are given in Figure 5, page 16 .

8.2 *Short-circuit current of the generators*

For each generator: $I_N = \dfrac{1\,000}{450\sqrt{3}} = 1.28$ kA.

$$I''_{\text{no load}} = \frac{I_N}{x''_d} = \frac{1.28}{0.15} = 8.53 \text{ kA.}$$

$$I'_{\text{no load}} = \frac{I_N}{x'_d} = \frac{1.28}{0.2} = 6.40 \text{ kA.}$$

The r.m.s. value of I_{ac} during the first few cycles can be obtained from formula (3):

$$I_{ac} = (I''-I')\,\varepsilon^{-t/T''} + I'$$

The frequency being 60 Hz, 1 cycle = 0.0167 s ; $\frac{1}{2}$ cycle = $\frac{1}{2}T = 8.3$ ms

$$(I''-I')_{\text{no load}} = 2.13 \text{ kA}$$

The values of I_{ac} and I_{dc} as a function of time t are given in Tables IV and V for the following values of t:

$$t = 0;\ \tfrac{1}{2}T;\ T;\ \tfrac{3}{2}T;\ 2\,T \text{ and } 3\,T$$

T being the time of one cycle.

TABLE IV

$T''_{gen} = 20$ ms. For decrement see Figure 7, page 22 , in which some particular values are given

t ms	$(I''-I')\,\varepsilon^{-t/T''}$ no load kA	I' no load kA	I_{ac} r.m.s. no load kA	I_{ac} rated load kA
0	2.13	6.4	8.53	9.38
$\frac{1}{2}T = 8.3$	2.13×0.65 = 1.38	6.4	7.78	8.55
$T = 16.6$	2.13×0.42 = 0.89	6.4	7.29	8.02
$\frac{3}{2}T = 25$	2.36×0.28 = 0.6	6.4	7.0	7.7
$2\,T = 33.2$	2.36×0.18 = 0.38	6.4	6.78	7.46
$3\,T = 50$	2.36×0.08 = 0.17	6.4	6.57	7.23

The d.c. component having at an instant $t = 0$, a value:

$\sqrt{2}\,I'' = 8.53\sqrt{2} = 12.1$ kA decreases as follows: $I_{dc} = \sqrt{2}\,I''\,\varepsilon^{-t/T_{dc}}$ (see formula (4)).

TABLE V

$T_{\mathrm{do\ gen}} = 40$ ms. For decrement $\varepsilon^{-t/T_{\mathrm{do}}}$ as function of time see Figure 7, page 22.
Table V contains a few particular values.

t ms	$I_{\mathrm{dc}} = f$ (time) kA
0	12.1
$\frac{1}{2} T = 8.3$	$12.1 \times 0.8 = 9.68$
$T = 16.6$	$12.1 \times 0.66 = 8$
$\frac{3}{2} T = 25$	$12.1 \times 0.53 = 6.4$
$2\ T = 33.2$	$12.1 \times 0.43 = 5.2$
$3\ T = 50$	$12.1 \times 0.28 = 3.4$

8.3 *Maximum possible peak value of the short-circuit current of the generators*

See formula 4 and Figure 2b, page 12.

According to Clause 1, for a fault occurring in close proximity to the main busbars, resistances may be neglected; though the power factor is very small and for determining the multiplying factor for $I_{\mathrm{peak\ max}}$ Figure 2b ($\cos \varphi = 0.05$) has to be used.

Figure 2b gives for $\frac{x'_{\mathrm{d}}}{x''_{\mathrm{d}}} = \frac{0.20}{0.15} = 1.33$, a factor $\frac{I_{\mathrm{peak}}}{I_{\mathrm{no\ load}}} = 2.5$;

where:

$$I_{\mathrm{peak\ max}} = 2.5 \times 7.78 = 19.5 \text{ kA}$$

According to formula 4, the maximum peak value can also be taken from Tables IV and V:

$$I_{\mathrm{peak\ max}} = 7.78\sqrt{2} + 9.68 = 11 + 9.68 = 20.68 \text{ kA}$$

8.4 *Short-circuit current of motors*

The most simple method for calculating motor contribution is the method given in Sub-clause 3.1 of Amendment No. 1 to IEC Publication 92-4, Electrical Installations in Ships, Part 4: Switchgear, Electrical Protection, Distribution and Controlgear (Chapter XIII) and formulae 5 and 6 of this Report are of one imaginary motor directly connected to the main busbars with a rated power equal to the sum of rated powers of all motors running simultaneously in service.

The motor contribution of this imaginary motor can, in point of fact, also be calculated with formulae 7 to 11 of this Report instead of the factors given in formulae 5 and 6.

These methods give only acceptable results if the motor power is principally concentrated in large units which are directly connected to the main busbars.

If the motor power is divided into only a few large units and many smaller ones all connected via long cables, then it may be more correct to make a separate calculation with the same formulae or factors for those points where the motor circuit-breakers are situated or motor power is concentrated. These various methods will be demonstrated as follows:

a) First method (see Figure 5, page 16, and Formulae 5 and 6)

Total motor power = 1 500 kVA, concentrated in one motor with the following parameters :

$$I_{N\,(\mathrm{motor})} = \frac{1\,500}{450\,\sqrt{3}} = 1.93\ \mathrm{kA}$$

The r.m.s. value of the motor contribution is calculated according to formula 5.

t	0	$\frac{1}{2}\,T$	T	$2\,T$
Factor	6.25	4	2.5	1
I_m (kA)	12	7.7	4.8	1.9

$$I_{\mathrm{peak\ max}} = 8\,I_N = 8 \times 1.93 = 15.5\ \mathrm{kA}$$

b) Second method

Total motor power = 1 500 kVA concentrated in one motor with the following parameters :

z_b = 0.16 impedance with rotor locked, in per cent
x_b = 0.155 reactance with rotor locked, in per cent
R_r = 0.0027 Ω
R_s = 0.0055 Ω

It follows :

$$Z_b = \frac{V_N}{I_N}\,z_b = \frac{260}{1\,930}\,0.16 = 0.0216\ \Omega$$

$$X_b = \frac{V_N}{I_N}\,x_b = \frac{260}{1\,930}\,0.155 = 0.0209\ \Omega$$

$$T'_d = \frac{0.0209}{2\,\pi\,60 \times 0.0027} = 0.0205\ \mathrm{s} = 20.5\ \mathrm{ms} \qquad \text{(see formula 7)}$$

$$T_{dc} = \frac{0.0209}{2\,\pi\,60 \times 0.0055} = 0.01\ \mathrm{s} = 10\ \mathrm{ms} \qquad \text{(see formula 8)}$$

$$I_{ac} = \frac{V_N}{Z_b}\,\varepsilon^{-t/T'} = \frac{260}{0.0216}\,\varepsilon^{-t/0.0205} = 12\,\varepsilon^{-t/0.0205} \qquad \text{(see formula 9)}$$

This value varies as a function of the time as shown in Table VI.

TABLE VI

$T'_{d\,(\mathrm{motor})}$ = 20.5 ms. For decrement see Figure 7, page 22.

t ms	$I_{ac\ \mathrm{motors}} = f\,(\mathrm{time})$ kA
0	12
$\frac{1}{2}\,T$ = 8.3	12×0.65 = 7.8
T = 16.6	12×0.42 = 5
$\frac{3}{2}\,T$ = 25	12×0.28 = 3.36
2 T = 33.2	12×0.18 = 2.16
3 T = 50	12×0.08 = 0.96

For $t = 0$, $I_{dc} = \sqrt{2}\ V_N/Z_b = \sqrt{2}\,(260)/0.0216 = 16.9$ kA.
This value varies as a function of the time as follows:

$$I_{dc} = \sqrt{2}\,\frac{V_N}{Z_b}\,\varepsilon^{-t/T_{dc}} = 16.9\ \varepsilon^{-t/0.010} \qquad \text{(see formula 10)}$$

TABLE VII

$T_{dc\ (motor)} = 10$ ms. For decrement see Figure 7, page 22.

t ms	$I_{dc\ motors} = f\,(\text{time})$ kA
0	16.9
$\frac{1}{2}\,T = 8.3$	$16.9 \times 0.43 = 7.25$
$T = 16.6$	$16.9 \times 0.2 = 3.4$
$\frac{3}{2}\,T = 25$	$16.9 \times 0.09 = 1.5$
$2\ T = 33.2$	$16.9 \times 0.01 =$ negligible
$3\ T = 50$	$16.9 \times =$ negligible

The maximum peak current at time $t = \frac{1}{2}\,T$ according to formula 11 is:

$$\sqrt{2}\ I_{ac} + I_{dc} = 7.8\,\sqrt{2} + 7.25 = 18.3\ \text{kA}$$

c) Third method

To be applied according to Sub-clause 8.5 and 8.6.

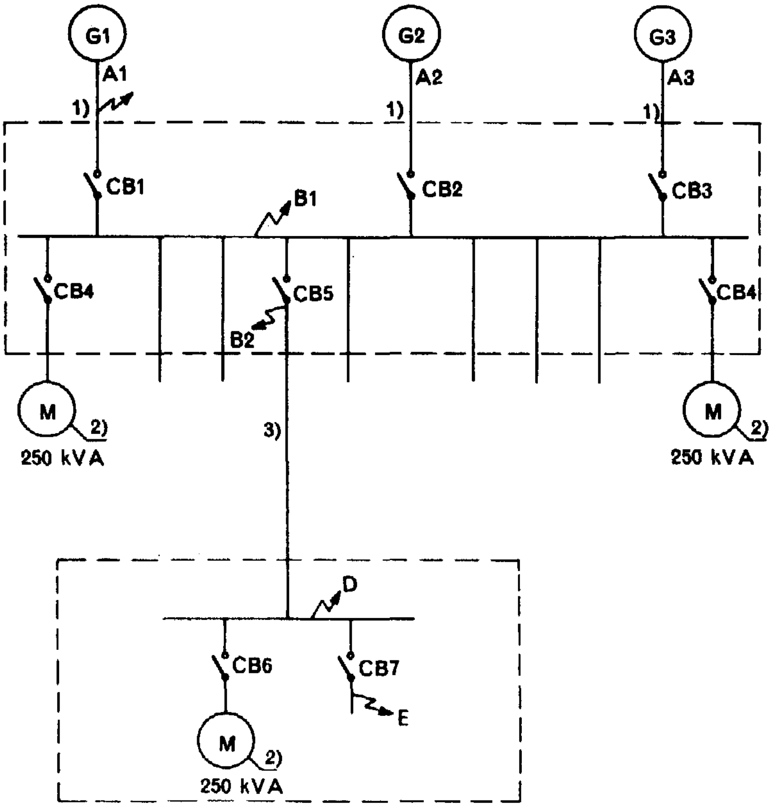


FIG. 5. — Hypothetical example.

For the generators : G1 = G2 = G3 1 000 kVA, $V_N = 450$ V, $f = 60$ Hz, cos $\varphi = 0.8$ at rated load.
$x''_d = 0.15$, $x'_d = 0.2$; $x_d = 1.15$, $T'' = 20$ ms, $T' = 400$ ms,
$T_{dc} = 40$ ms.

For the motors : Total motor power which may be running simultaneously in service is 1 500 kVA equal to 50% of the total power of the generators. There are two motors of 250 kVA directly connected to the main busbars and one large motor of 250 kVA connected to a section board via a cable of 100 m.

1) 20 m cable, $4 \times 3 \times 180$ mm^2 ; $R = 0.65 \times 10^{-3}\ \Omega$; $X = 0.46 \times 10^{-3}\ \Omega$.
2) Motor of 250 kVA, $V_N = 450$ V, $z_b = 0.16$; $T'_d = 0.02$; $x_b = 0.155$; $T_{dc} = 0.01$.
3) 100 m cable, 3×180 mm^2, $R = 13 \times 10^{-3}\ \Omega$; $X = 9.2 \times 10^{-3}\ \Omega$.

8.5 *Evaluation of the maximum value of the short-circuit current in case of fault near the main busbars*

The actual peak current is the arithmetical sum of the peak values separately evaluated for the generators and for the motors. For the generator circuit-breakers CB1, CB2 and CB3 (see Figure 5, page 16), Sub-clause 6.2 of Amendment No. 1 to IEC Publication 92-4 (Chapter XIII) should be taken into account.

With a short-circuit at Point A1, CB1 has to break the sum of the short-circuit currents of G2, G3 and the motor contribution.

a) First method

The first method is given already in Clause 8.4.

b) Second method

Short-circuit at Point A1

$$I_{ac\ total} = I_{ac\ gen} + I_{ac\ motor\ contribution}$$

t kA	0	$\frac{1}{2}T$	T	$\frac{3}{2}T$	$2T$	$3T$
$I_{ac\ 2\ gen}$ * $I_{ac\ motor}$ **	18.75 12	17.1 7.8	16 5	15.4 3.36	15 2.16	14.5 0.96
$I_{ac\ total}$	30.75	24.9	21	18.8	17.2	15.5

* $I_{ac\ 2\ gen} = 2\ I_{ac\ rated\ load}$ (see Table IV).
** See Table VI.

The figures given for the generators are taken from Table IV and multiplied by 2.
The figures for the motors are taken from Table VI. For $I_{peak\ total}$ see Sub-clauses 8.3 and 8.4.

$$I_{peak\ total} = 2\ I_{peak\ gen} + I_{peak\ motor} = 2 \times 20.68 + 18 \cong 60\ \text{kA}.$$

This means that CB1, CB2 and CB3 should have a rated breaking capacity of 24.9 (25) kA and a rated making capacity of 60 kA.
In this calculation, the influence of the cables between the generators and the main switch board is neglected. A rapid check shows that the sub-transient reactance of one generator is $X_r = 30.5$ mΩ ; $X_{cable} = 0.46$ mΩ and $R_{cable} = 0.64$ mΩ.
These cable values, which are hardly 1.5% of X'' affect the total I only to a very small degree, so that they may be neglected in the calculation for the r.m.s. value.

Short-circuit at Points B1-B2 (see Figure 5, page 16) :

The calculation with regard to the main switchboard may thus be started with the same values as valid for Points A1, A2, A3. Also, the values of T''_d and T'_d are not affected by the insertion of these cables. Only T_{dc} and in consequence, the decrease of the d.c. component is influenced by the resistance of the cable concerned and as a consequence, the asymmetrical value $I_{peak\ max}$.

For one generator $V_N = 260$ V, $I_N = 1\,280$ A.

$$x'' = 0.15, \qquad X'' = \frac{260}{1\,280}\,0.15 = 0.0305\ \Omega,$$

$$T_{dc} = 40\ \text{ms} = \frac{L}{R} = \frac{\omega L}{\omega R} = \frac{X''}{\omega R_s},$$

$$R_s = \frac{X''}{\omega T_{dc}} = \frac{0.0305}{2\pi 60 \times 0.04} \cong 0.002\ \Omega,$$

$$R_{cable} = 0.000\,64\ \Omega, \qquad X_{cable} = 0.000\,46\ \Omega,$$

from formula 15, we have :

$$T_{e_{dc}} = \frac{T_{dc} + (x_e/\omega R_s)}{1 + (R_e/R_s)} = \frac{0.04 + (0.000\,46/2\pi 60 \times 0.002)}{1 + \frac{1}{2}\,(0.000\,64)} \cong 0.031\ \text{s} = 31\ \text{ms}$$

With this new time constant, the values of Table V change as follows :

$$I_{dc} = \sqrt{2}\,;\, I''\,\varepsilon^{-t/0.031}$$

TABLE VIII

$T_{e_{dc\ (gen)}} = 31$ ms. For decrement see Figure 7, page 22.

t ms	$I_{dc} = f$ (time) kA
0	12.1
$\frac{1}{2}\,T = 8.3$	12.1 × 0.76 = 9.1
$T = 16.6$	12.1 × 0.58 = 7
$\frac{3}{2}\,T = 25$	12.1 × 0.44 = 5.3
$2\,T = 33.2$	12.1 × 0.34 = 4.1
$3\,T = 50$	12.1 × 0.18 = 2.2

Though the d.c. time constant has decreased by cable insertion from 40 ms to 31 ms, it appears when comparing Table V with Table VIII, that I_{peak} is not strongly influenced.

The calculated value with a time constant of 31 ms for I_{peak} is :

$I_{peak\ gen} = 7.78\,\sqrt{2} + 9.1 = 11 + 9.1 = 20.1$ kA, instead of 20.68 kA.

The circuit-breakers CB4, CB5, etc., situated in the outgoing lines of the main switchboard have to withstand, when concentrating the total motor power on the main busbars, a total symmetrical value of :

t kA	0	$\frac{1}{2}\,T$	T	$\frac{3}{2}\,T$	$2\,T$	$3\,T$
$I_{ac\ 3\ gen}$	28	25.6	24	23	22.5	21.7
$I_{ac\ 1\ motor}$ *	12	7.8	5	3.36	2.16	0.96
$I_{ac\ total}$	40	33.4	29	26.4	24.7	22.7

*See Table VI.

The figures of the first line are taken from Table IV and multiplied by three.

$I_{\text{peak total}} = I_{\text{peak 3 gen}} + I_{\text{peak motor}} = 3 \times 20.1 + 18 \cong 78$ kA.

This means that CB4, CB5 etc. should have a rated breaking capacity of 33.4 (34) kA and a rated making capacity of 78 kA.

8.6 *Evaluation of the short-circuit current in case of fault remote from the main busbars*

Fault at Point D, calculated without motor contribution. In Figure 6, the simplified scheme is given.

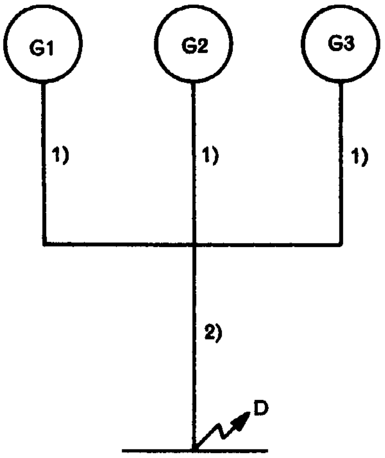


FIGURE 6

1) 20 m cable 4×3×180 mm².
2) 100 m cable 3×180 mm².

$X''_{\text{gen}} = 0.0305\ \Omega$; $R_{\text{gen}} = 0.002\ \Omega$.

The impedances of the cables are the following:

— cables of 20 m coming from the generators:
$X = 0.000\,46\ \Omega$; $R = 0.000\,65\ \Omega$;

— cables between main switch board and section board (100 m of 3×180 mm²).

The total impedance is:

$X = 0.0092\ \Omega$, $R = 0.013\ \Omega$,

$X_{\text{total}} = \frac{1}{3}(0.0305 + 0.000\,46) + 0.0092 \cong 0.0195\ \Omega$,

$R_{\text{total}} = \frac{1}{3}(0.002 + 0.000\,65) + 0.013 = 0.0139\ \Omega$,

$Z''_{\text{e}} = \sqrt{0.0195^2 + 0.0139^2} = 0.024\ \Omega$,

For $t = 0$, I''_{e} at point D $= 260/0.024 = 11$ kA.

To find Z' and I', value X'' should be taken instead of X' in Figure 6.

$X'_{\text{total}} = \frac{1}{3}(0.041 + 0.000\,46) + 0.0092 = 0.0232\ \Omega$ and $R_{\text{total}} = 0.0139\ \Omega$.

$Z'_{\text{e}} = \sqrt{0.0232^2 + 0.0139^2} = 0.027\ \Omega$.

I'_{e} at point D $= 260/0.027 = 9.6$ kA.

It is clear that in this case, it is not necessary to use formula 16 but to state that $I_{ac} = 11$ kA (because the value of $(I''-I')$ is very small).
This would be the maximum value of $11\sqrt{2} = 15.5$ kA. $I_{peak\ max}$ should be in accordance with formula 17.

$$I_{peak\ max} = I_{ac}\sqrt{2} + I_{ac}\sqrt{2}\ \varepsilon^{-t/2\,T_{dc}}$$

New time constant $T_{e_{dc}}$ has to be calculated with formula 15 :

$$T_{e_{dc}} = \frac{T_{dc} + \dfrac{X_e}{\omega R_s}}{1 + \dfrac{R_e}{R_s}} = \frac{0.04 + \dfrac{0.0092 + \frac{1}{3}(0.000\,46)}{2\pi\,60 \times \frac{1}{3}(0.002)}}{1 + \dfrac{\frac{1}{3}(0.000\,65) + 0.013}{0.000\,65}} = 0.0037 \text{ s} = 3.7 \text{ ms}$$

The d.c. component of the asymmetrical current varies with a time constant of 3.7 ms as follows :

TABLE IX

$T_{e_{dc}\,(motor)} = 3.7$ ms. For decrement see Figure 7, page 22.

t ms	$I_{dc} = f$(time) at Point D kA
0	$11\sqrt{2} = 15.5$
$\frac{1}{2}T = 8.3$	$15.5 \times 0.1 = 1.55$
$T = 16.6$	$15.5 \times 0.01 = 0.15$

I_{peak} at $t = \frac{1}{2}T$ for Point D and without motor contribution is equal to :

$$I_{ac}\sqrt{2} + I_{dc} = 15.5 + 1.55 \cong 17 \text{ kA}$$

From this calculation, it can be seen that the d.c. component (time constants of a few ms and small amplitude) has practically disappeared.

8.7 *Motor contribution in Points D and E :*

Now referring to the discussion under Sub-clause 4.1 dealing with concentrated or not concentrated motor power on the main busbars, it is supposed as given in Figure 5, page 16, that one of the large motors (250 kVA) is connected to the section board.
To simplify the calculation, the same parameters have been taken for the motor 250 kVA as for the imaginary motor of 1 500 kVA. This means that all values given in Tables VI and VII are valuable if divided by six.
Thus for the motor contribution of one motor of 250 kVA connected to the section board and with a short-circuit in Point D or E, the following values count (see Sub-clause 8.4) :

TABLE X

$T'_{d\,(motor)} = 20.5$ ms. For decrement see Figure 7.

t ms	$I_{ac\ motor\ 250\ kVA} = f$(time) kA
0	2
$\frac{1}{2}T = 8.3$	$2 \times 0.64 = 1.28$
$T = 16$	$2 \times 0.42 = 0.84$
$\frac{3}{2}T = 25$	$2 \times 0.28 = 0.56$
$2\ T = 33.2$	$2 \times 0.18 = 0.36$
$3\ T = 50$	$2 \times 0.08 = 0.16$

TABLE XI

$T_{\text{dc (motor)}}$ = 10 ms. For decrement see Figure 7, page 22 and Sub-clause 8.4*b*), page 15 .

t ms	$I_{\text{dc motor 250 kVA}} = f\,(\text{time})$ kA
0	2.82
$\frac{1}{2}T = 8.3$	$2.82 \times 0.43 = 1.2$
$T = 16$	$2.82 \times 0.2 = 0.56$
$\frac{3}{2}T = 25$	2.82×0.09 = negligible
$2\,T = 33.2$	2.82×0.01 = negligible
$3\,T = 50$	

$I_{\text{peak max}} = I_{\text{ac}} + I_{\text{dc}} = 1.28\sqrt{2} + 1.2 = 3$ kA.

I_{ac} with motor contribution and a short-circuit in D or E is as a result of this, not 11 kA, bu $11 + 1.28 = 12.28$ kA.

With motor contribution at Point D or E, $I_{\text{peak max}} = 17 + 3 = 20$ kA.

Finally, a calculation with all the motor power of 1 500 kVA again concentrated on the busbar and a short-circuit in Point D. The motor contribution is then strongly reduced by the long cabl (100 m in 3×180 mm²).

$T_{\text{dc motor}} = 0.01$ s. This corresponds with a $\cos\varphi = 0.25$. Further on :

$$\left.\begin{aligned} Z &= 0.0216\,\Omega \\ X &= 0.0209\,\Omega \\ R &= 0.0055\,\Omega \end{aligned}\right\}\ \text{motor 1 500 kVA,}$$

$R_{\text{cable}} = 0.013\,\Omega$,

$X_{\text{cable}} = 0.0092\,\Omega$.

According to formula 15, the new value of T_{dc} is :

$$T_{e_{dc}} = \frac{0.01 + (0.0092/2\pi 60 \times 0.0055)}{1 + (0.013/0.0055)} = 0.0043 \text{ s} = 4.3 \text{ ms}$$

From Table IX it can be concluded that with a small time constant (about 4 ms) the d.c. component decreases so fast that I_{dc} can be neglected.

According to formula 9 :

$$I_{\text{ac}} = \frac{V_{\text{N}}}{Z_{\text{b}}}\,\varepsilon^{-t/T'}$$

Z_{b} witn cable is :

$$Z_{\text{b}} = \sqrt{(0.0209 + 0.0092)^2 + (0.0055 + 0.013)^2} = 0.0354\,\Omega$$

$$I_{\text{ac}} = \frac{0.026}{35.4}\,\varepsilon^{-t/T'} = 7.35\,\varepsilon^{-t/T'}$$

for $t = \frac{1}{2}T$:

$$I_{\text{ac motor}} = 7.35\,\varepsilon^{-t/2T'} = 7.35 \times 0.64 = 4.7 \text{ kA}$$

In this case, the breaking capacity of the breakers, having an opening time of $\frac{1}{2}T$ and situate in Point D should be $11 + 4.7 = 15.7$ kA symmetrical (no asymmetrical value).

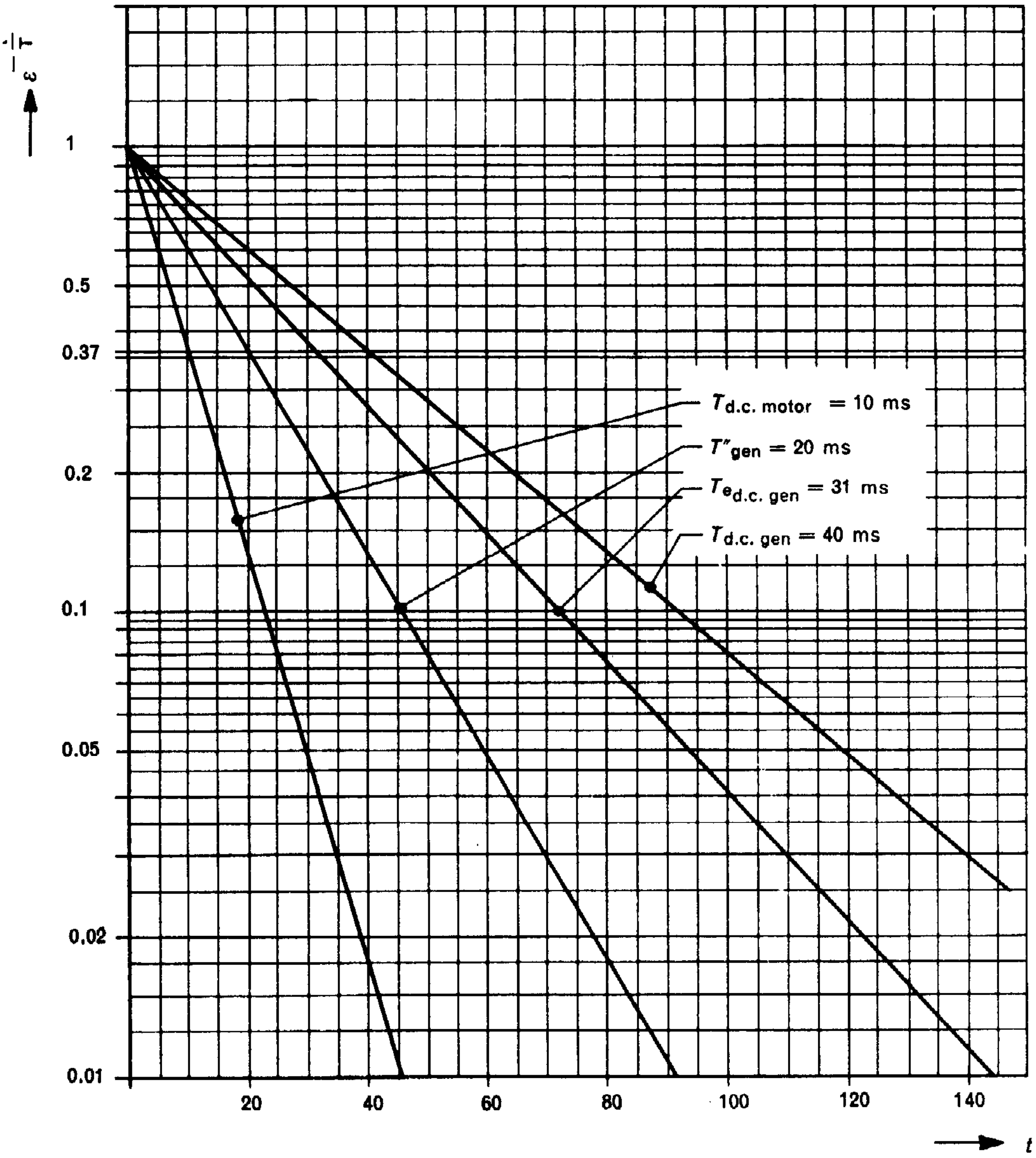
From this example, it appears that generally at a distance from the main busbars there is n question of a d.c. component.

Whether or not there is a d.c. component can be easily established by using formula 15 to calculat the new time constant $T_{e_{dc}}$. If this value is smaller than 5 ms the d.c. component can certainl be neglected. By means of the formulae given in this Report any symmetrical or asymmetrical current at any place can be calculated.

Note. — The values of all the ε functions are read from a diagram. From the form $\varepsilon^{-t/T} = f(t)$ can be inferred that log $\varepsilon^{-t/T}$ decreases proportionally to t.
When $\varepsilon^{-t/T}$ is plotted to a logarithmic scale and t to a linear scale, the function $\varepsilon^{-t/T} = f(t)$ can be represented by a straight line, of which two points are known :

— for $t = 0$: $\varepsilon^{-t/T} = 1$,
— for $t = T$: $\varepsilon^{-t/T} = 1/\varepsilon = 0.368$.

This function can be plotted in a simple way to the above scale. This is done for the generator in Figure 7, and can be done for every value of T required.



Decrement $\varepsilon^{-t/T} = f(t)$

FIG. 7. — Values of the decrement with the time.

SECTION TWO — D.C. PLANTS

9. List of main letter symbols

9.1 *Plants in general*

P	basic power, in kilowatts.
V_N	rated voltage, in volts.
I_N	rated current, in amperes.
i_N	rated current, in percent.
I_a	short-circuit current at time t, in amperes.
$i_{a.r.}$	short-circuit current at time t, in percent.
I_p	short-circuit current peak value, in amperes.
$I_{p.r.}$	short-circuit current peak value, in percent.
L'	initial inductance, in henry.
l'	initial inductance, in percent.
R'	resistance, in ohms.
r'	resistance, in percent.
R_e	resistance of connections, in ohms.
r_e	resistance of connections, in percent.
L_e	inductance of connections, in henry.
l_e	inductance of connections, in percent.
T_e	time constant, in seconds.
t	time taken from the instant zero, in correspondence of which the short-circuit current is calculated in seconds.

9.2 *Machines*

P_N	rated power in kilowatts.
E_0	internal voltage, in volts.
e_0	$= E_0/V_N$ internal voltage, in percent.
R'_d	armature transient resistance, in ohms *.
r'_d	armature transit resistance per unit (or in %) *.
L'_a	initial (or non-saturated) armature inductance, in henry.
l'_a	initial (or non-saturated) armature inductance, in percent.
T_a	$= L'_a/R'_d = l'_a/r'_d$ armature time constant, in seconds.

Note. — The following formula is used to obtain the per cent value from the actual values of resistances R :

$$r = R \frac{P}{V_N^2} \text{ in percent,}$$

$$\text{similarly for inductance } l = L \frac{P}{V_N^2}$$

The short-circuit current is obtained by multiplying the current per unit values by the rated current I_n. By means of the following formula, it is possible to obtain one per unit value from another :

$$r_{II} = r_I \frac{P_{II}}{P_I}$$

where I and II in symbols indicate respectively the known per unit value and the per unit value to be calculated, referred to the base power.

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* The transient resistance is that value of resistance which occurs at the short-circuit peak current, includes all the various resistances of the machines limiting the current flow, and takes into account the decrement of the air gap flux up to the instant of the peak of short-circuit current. Thus the voltage V_N may be regarded as constant up to the instant of the peak of short-circuit current.

10. Short-circuit at the terminals of a d.c. generator

The characteristics and the short-circuit current peak value of a d.c. generator previously running at rated load * are expressed by means of the formulae given below.

The decrement which occurs after the current has attained the peak value is not of interest as regards the choice of the circuit-breakers in the installation.

10.1 *Short-circuit current peak value*

$$I_{pr} = \frac{e_0}{r'_d}, \ \% \qquad (21)$$

10.2 *Short-circuit current characteristics up to peak value* **

$$i_{a.r.} = I_{p.r.} \left(1 - \varepsilon^{-t/T_a}\right), \ \% \qquad (22)$$

where :

$$T_a = \frac{L'_a}{R'_d} = \frac{l'_a}{r'_d}, \text{ in seconds} \qquad (23)$$

11. Short-circuit at the terminals of a motor

The characteristics and the short-circuit current peak value of a motor are also expressed by formulae (21), (22) and (23) used for a d.c. generator.

12. Short-circuit far from the terminals of electrical machines

When a short-circuit occurs at a distance remote from the terminals of electric machines (generators and motors), external resistances and inductances are to be added in the internal ones.

The formulae 24, 25 and 26 are used instead of 21, 22, 23 respectively.

12.1 *Short-circuit current peak value*

$$I_{p.r.} = \frac{e_0}{r'_d + r'_e}, \ \% \qquad (24)$$

12.2 *Short-circuit current characteristics up to peak value*

$$i_{a.r.} = I_{p.r.} \left(1 - \varepsilon^{-t/T_e}\right), \ \% \qquad (25)$$

where :

$$T_e = \frac{L'_a + L_e}{R'_d + R_e} = \frac{l'_a + l_e}{r'_d + r_e} \text{ s} \qquad (26)$$

13. Short-circuit in an installation

The most complex case of short-circuit occurs when a number of generators and motors exist in an installation all feeding the short-circuit.

The calculation of the short-circuit current at the different points of an installation is to be made :

- at the terminals of machines : (Point A, Figure 9, page 31) taking into consideration only transient resistances and initial inductances in the armature circuits ;
- on the outgoing feeders of each machine : (Point A', Figure 9) considering the inductances and resistances of the machines and feeders as far as the point involved ;
- on the main switchboard outgoing feeders just after the protection breaker (Point B, Figure 9) by adding the contribution of motors and generators (calculated separately) Figure 12, page 34 ;
- on the sub-switchboard outgoing feeders (Point C, Figure 9).

---

* The rated load condition is taken to be the most unfavourable with respect to short-circuit. The formulae in this report are based on some simplifications and neglecting the action of voltage regulator, if any.

** The transient current is in fact controlled by a time constant which can only roughly be supposed equal to T_a.

This calculation can be made assuming only that the total short-circuit current at Point B corresponds to that of one equivalent generator having a voltage V_N and a short-circuit current equal to the sum of the contributions of all the generators and motors considered (Figure 12, page 34).

The resistance of connections can have a determining effect upon the values to be calculated ; also, the calculation of the time constant of the whole part of the installation located on the source side can only be made by means of simplifying assumptions.

In practice, it is sufficient in most cases to calculate only the peak value I_p by determining the total resistance R'_C or r'_C as the sum of resistance R'_B or r'_B (corresponding to the peak value of the short-circuit current at Point B) and of the resistance of connections R_e or r_e.

If it is necessary to determine also the current characteristic, the calculation could be made as shown in the following example.

14. Calculation by means of coefficients

14.1 *Short-circuit at the terminals of a generator or of a motor*

When the transient resistance R'_d and inductance L'_a values are not available, the calculation can be made using the values of the Figures 10, 13 and 14 on pages 32, 35 and 36 respectively.

14.1.1 *Peak value*

$$I_{p.r.} = \frac{e_0}{r'_d} \% \qquad (27)$$

where :

r'_d = the armature transient resistance, in per cent, drawn from the diagram of Figure 10 in function of the product of rated power in kilowatts by angular velocity in revolutions per minute.

14.1.2 *Characteristics up to peak value*

$$i_{a.r.} = d\, I_{p.r.} \% \qquad (28)$$

where :

$d = 1 - \varepsilon^{-t/T_a}$ is the multiplication factor drawn either from Table XII below, or from Figure 11, page 31 in function of ratio $\frac{t}{T_a}$.

TABLE XII

Multiplying factor d

$\frac{t}{T_a}$	0	0.1	0.2	0.5	1.0	1.5	2	3	4	5
d	0	0.095	0.181	0.394	0.632	0.777	0.865	0.95	0.982	0.993

$T_a = \frac{L'_a}{R'_d} = \frac{l'_a}{r'_d}$ armature time constant, in seconds

$L'_a = C\, V_N^2$ initial armature inductance, in henry

where C is a multiplying factor drawn from Figures 13 and 14, pages 35 and 36.

14.2 *Short-circuit far from the machine terminals*

Calculation is to be made as described in Clauses 12 and 13.

15. Example of calculation

15.1 *Data*

The example given below serves only to explain how the various formulae are used for the calculation of the short-circuit current at Points A, A′, B and C of the installation shown in Figure 9, page 31. This example is hypothetical and does not represent any existing installation :

a) For the generators

— Number of generators running in parallel $N = 2$
— Rated power $P_g = 200$ kW
— Power * $P = 200$ kW
— Current $I = 870$ A
— Voltage $V_N = 230$ V
— Internal voltage $e_o = 1.03\%$
— Rated current $I_N = 870$ A
— Rated speed of rotation $n = 350$ rev/min
— Number of poles $p = 8$
— Polyphase winding none
— Power × speed of rotation product $P_g n = 70\,000$ kW rev/min
— Armature circuit transient resistance $r'_d = 0.12\%$
$R'_d = 0.0315\ \Omega$
— Armature circuit initial non-saturated inductance $L'_a = 0.001$ H
$l'_a = 0.00378\%$

b) For the motors

— Power of the motors assumed in service at the instant when the short-circuit occurs equal to 60% of the total power of generators $P_m = 255$ kW
— Average power of the motors ** $P_{ma} = 15$ kW
— Machine internal voltage (average value) $e_o = 0.93\%$
— Total rated current $I_m = 1\,100$ A
— Rated speed of rotation (average value) $n = 1\,500$ rev/min
— Number of poles $p = 4$
— Power × rev/min product $P_{ma}\, n = 22\,500$ kW rev/min
— Armature circuit transient resistance $r'_d = 0.127\%$ †

$$R'_{dm} = r'_d \frac{V_N^2}{P_m} = 0.027\ \Omega$$

$$r'_m = r'_d \frac{P}{P_m} = 0.1\%$$

— Armature circuit initial inductance $L'_{am} = C\, V_N^2 = 0.000\,245$ H
$l'_{am} = 0.0012\%$ †

c) For connections

— *Cable 1* (Figure 9) $l'_m = 0.000\,94\%$ ††
— Length 2 × 15 m
— Cross-section area 4 parallel cables, 1 × 160 mm^2 (per phase)

---

* This value can be chosen arbitrarily : usually, however, it is assumed equal to the power of one generator.

** When the characteristics of each motor are not known it is advisable to define the average power value in order to obtain the value of r'_d from the curves on Figure 10, page 32.

† Referred to P_m.

†† Referred to $P = 200$ kW.

— Resistance $R_{e_1} = 0.001\,04\ \Omega$

$r_{e_1} = R_{e_1}\dfrac{P}{V_N^2} = 0.0039\%$

— Inductance $L'_{e_1} = 0.002\times10^{-3}$ H

$l'_{e_1} = \dfrac{L_{e1}\,P}{V_N^2} = 0.000\,007\,58\%$

— *Cable 2* (Figure 9) page 31

— Length 2×40 m

— Cross-section area 1×160 mm^2 (per phase)

— Resistance $R_{e_2} = 0.011\ \Omega$

$r_{e_2} = R_{e_2}\dfrac{P}{V_N^2} = 0.041\%$

— Inductance $L_{e_2} = 0.02\times10^{-3}$ H

$l_{e_2} = 0.000\,07\%$

15.2 *Short-circuit current on the d.c. generator terminals at Point A*

Note. — The calculation is for the generator contribution only. If it is required to find the total short-circuit at Point A, it will be necessary to add the contribution from other machines.

15.2.1 *Peak value*

From formula (1), we obtain :

$$I_{\text{p.r.}} = \frac{e_0}{r'_d} = \frac{1.03}{0.12} = 8.6\%$$

$$I_{\text{p.A.}} = I_{\text{p.r.}}\,I = 8.6\times0.87 \approx 7.5\ \text{kA}$$

15.2.2 *Characteristics up to the peak value*

From formula (2), we obtain :

$$T_a = \frac{l_a}{r_d} = \frac{0.003\,78}{0.12} = 0.032\ \text{s} = 32\ \text{ms}$$

$$i_{\text{a.r.}} = 8.6\,(1-\varepsilon^{-t/0.032})\%$$

This value varies in function of the time as follows :

TABLE XIII

t s	0	0.001	0.002	0.005	0.010	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16
$\frac{t}{T_a} \approx$	0	0.031	0.063	0.156	0.312	0.624	1.25	1.87	2.50	3.12	3.75	4.37	5.00
$i_{\text{a.r.}} \approx$ %	0	0.266	0.525	1.25	2.30	4.00	6.15	7.25	7.90	8.20	8.35	8.50	8.55
$i_a \approx$ kA	0	0.23	0.46	1.10	2.00	3.50	5.30	6.35	6.90	7.13	7.26	7.40	7.45

15.3 *Short-circuit at Point B*

15.3.1 *Contribution of generators at Point B*

a) Peak value

$$I_{\text{p.r.}} = \frac{e_0}{r'_d + r_{e_1}} = \frac{1.03}{0.12 + 0.0039} = 8.3\%$$

$$I_{\text{p.A.}'} = I'_{\text{p.r.}}\,I = 8.3\times0.87 \approx 7.2\ \text{kA}$$

b) Characteristics up to the peak value

From the formula (2) we obtain :

$$T_e = \frac{l'_a + l_{e_1}}{r'_d + r_e} = \frac{0.003\,78 + 0.000\,007\,6}{0.12 + 0.0039} = 0.031 \text{ s} = 31 \text{ ms}$$

$$i_{a.r.} = 8.3\,(1 - \varepsilon^{-t/0.031})\%$$

This value varies in function of the time as follows :

TABLE XIV

t s	0	0.001	0.002	0.005	0.010	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16
$\frac{t}{T_e} \approx$	0	0.032	0.064	0.161	0.322	0.645	1.29	1.94	2.58	3.22	3.88	4.52	5.16
$i_{a.r.} \approx$ %	0	0.266	0.515	1.25	2.30	3.9	6.0	7.10	7.7	8.0	8.1	8.2	8.25
$i_a \approx$ kA	0	0.23	0.45	1.10	2.0	3.4	5.2	6.2	6.7	7.0	7.05	7.15	7.18

15.3.2 *Contribution of motors at Point B*

The calculation is made assuming that the sum P_m of the rated powers of the different motors in service at a time is equal to 255 kW and that all the motors with $P_{ma} = 15$ kW, $n = 1\,500$ rev/min, $p = 4$ are directly connected to the main busbars with cables having negligible resistances and inductances *.

a) Peak value

From the formula (21) we obtain :

$$I_{p.r.} = \frac{e_o}{r'_m} = \frac{0.93}{0.10} = 9.1\%$$

$$I_p = I_{p.r.}\, I = 9.1 \times 0.87 \approx 7.9 \text{ kA}$$

b) Characteristics up to the peak value

From the formula (22) we obtain :

$$T_m = \frac{l_m}{r'_m} = \frac{0.000\,94}{0.1} = 0.0094 \text{ s}$$

$$i_{a.r.} = 9.1\,(1 - \varepsilon^{-t/0.009})\%$$

This value varies as a function of time as follows :

TABLE XV

t s	0	0.001	0.002	0.003	0.005	0.01	0.02	0.03	0.04	0.05
$\frac{t}{T_m}$	0	0.111	0.222	0.333	0.555	1.11	2.22	3.33	4.44	5.55
$i_{a.r.}$ %	0	0.955	1.81	2.56	3.88	6.18	8.00	8.76	9.00	9.05
$i_a \approx$ kA	0	0.83	1.58	2.20	3.40	5.40	6.95	7.60	7.83	7.87

---

* In practice the resistances and inductances of cables are not always negligible. However, the calculation is rather complex due to the quantity of cables.

15.3.3 *Characteristics and peak value of the total short-circuit current at Point B*

The characteristics and peak value of the short-circuit at Point B can be easily determined graphically by adding the time current diagrams of each machine (Figure 12, page 34).

15.4 *Short-circuit current at any point of the installation (C) far from main busbars*

As stated in Clause 13, the calculation of the characteristic up to the peak value requires some simplification and is not strictly necessary.

From the curve of Figure 12, the following values can be graphically obtained:

$$I_{p.r.} = 25.7 \text{ p.u.}, \quad I_{p.B.} = 22.3 \text{ kA}, \quad T_B = 21 \text{ ms}$$

$$\left(\frac{dI_{p.B.}}{dt}\right)_{t=0} = \frac{I_{p.B.}}{T_B} = 1.06 \times 10^6 \text{ A/s}$$

which gives the total value of transient resistance and of initial inductance:

$$R'_B = \frac{V_N}{I_{p.B.}} = 0.0103 \; \Omega$$

$$r'_B = R'_B \frac{P}{V_N^2} = 0.039\%$$

$$L'_B = V_N \Big/ \left(\frac{dI_{p.B.}}{dt}\right)_{t=0} = 0.000\,216 \text{ H}$$

15.4.1 *Peak value*

$$I_{p.r.} = \frac{1}{r'_C} = \frac{1}{0.08} = 12.5\%$$

$$r'_C = r'_B + r_{e2} = 0.039 + 0.041 = 0.08\%$$

$$I_{p.C.} = I_{p.r.}\, I = 12.5 \times 0.87 = 10.9 \text{ kA}$$

15.4.2 *Characteristics up to the peak value*

Note. — If a calculation of the current characteristic is required, the following procedure should be adopted:

$$i_{a.r.} = 12.5\,(1 - \varepsilon^{-t/T_c})\%$$

where:

$$T_c = \frac{l'_B + l_{e2}}{r'_B + r_{e2}} = \frac{0.000\,815 + 0.000\,07}{0.039 + 0.041} = 0.011 \text{ s} = 11 \text{ ms}$$

This value varies as a function of time as follows:

TABLE XVI

t s	0	0.001	0.002	0.003	0.005	0.010	0.015	0.020	0.030	0.040	0.050	0.060
$\frac{t}{T_c} \approx$	0	0.095	0.190	0.286	0.476	0.952	1.43	1.90	2.86	3.81	4.76	5.72
$i_{a.r.} \approx$ %	0	1.04	2.20	3.10	4.73	7.67	9.50	10.62	11.68	12.22	12.40	12.46
$i_a \approx$ kA	0	0.90	1.92	2.70	4.10	6.65	8.25	9.25	10.15	10.65	10.80	10.84

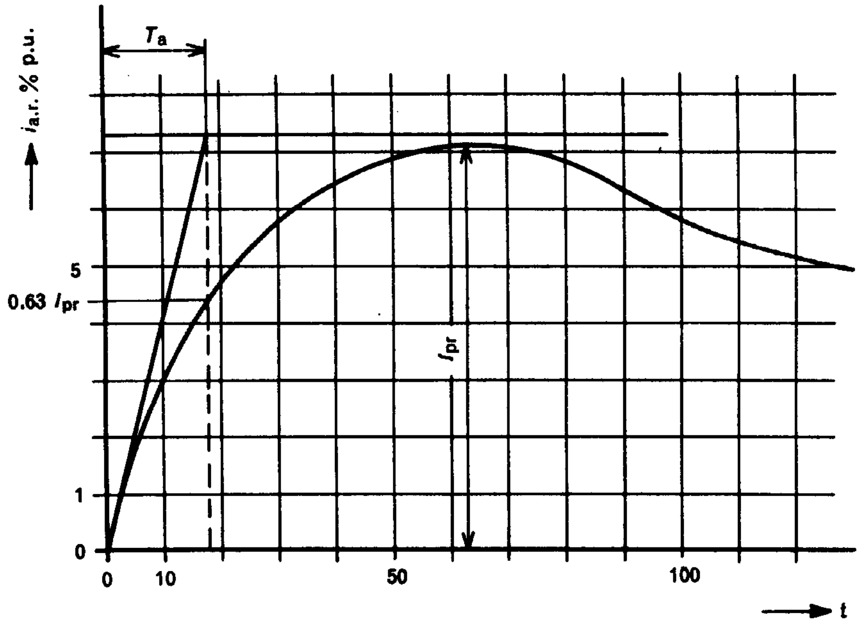


FIG. 8. — Short-circuit characteristic at the terminals of d.c. machines.

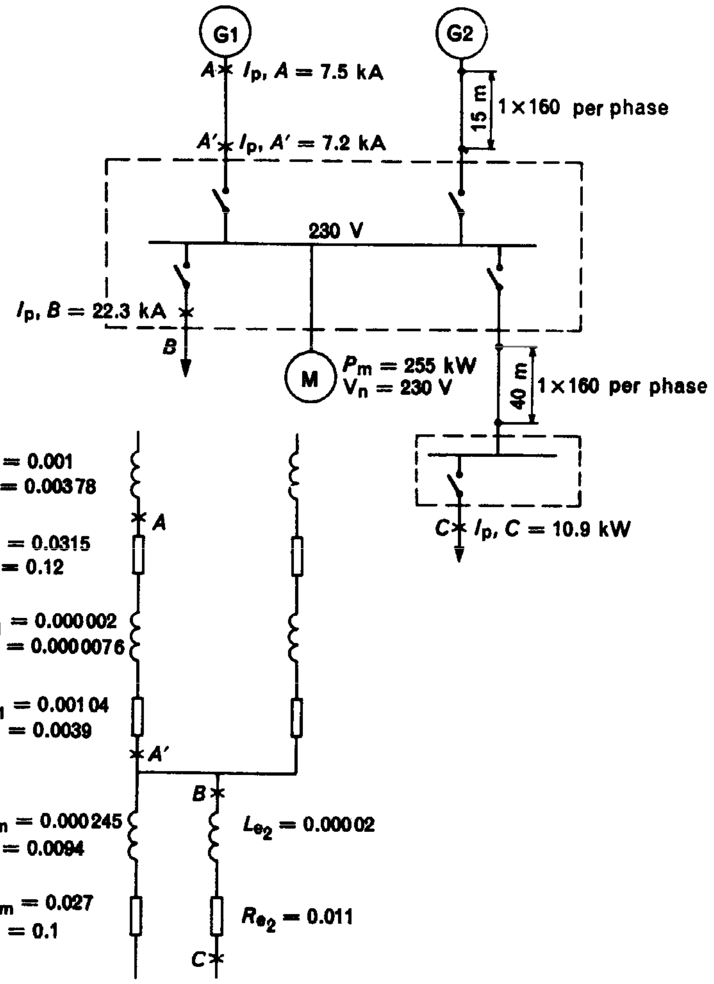
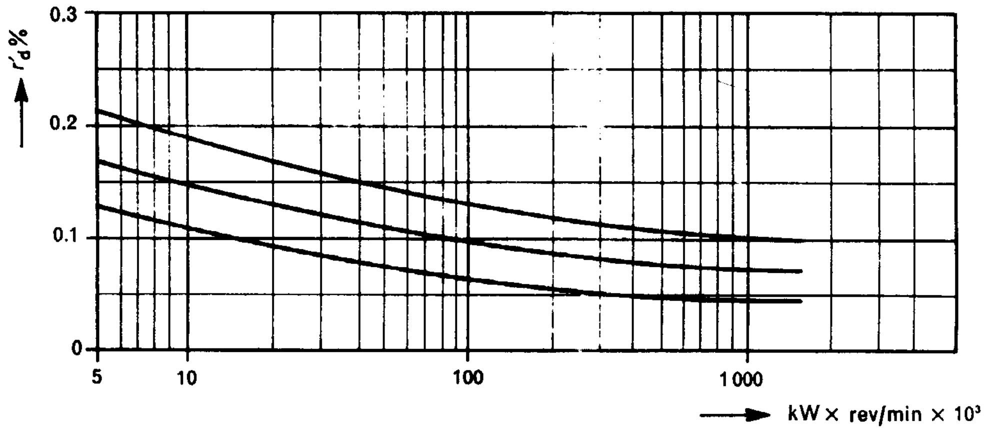


FIG. 9. — Simplified diagram of an installation for the evaluation of the short-circuit current values.



Note. — This figure is suitable for all machines having a voltage rating in the range from 115 V to 750 V. The value of r'_d for the lower voltage machine will usually be nearer the upper curve and for the higher voltage machine will be nearer the lower curve.

FIG. 10. — Diagram for the determination of per cent transient armature resistance.

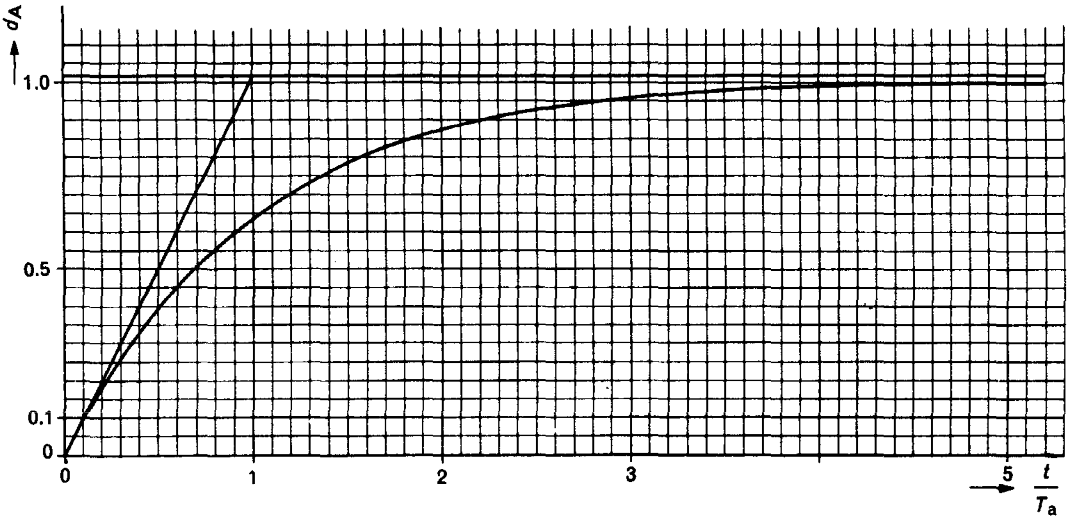
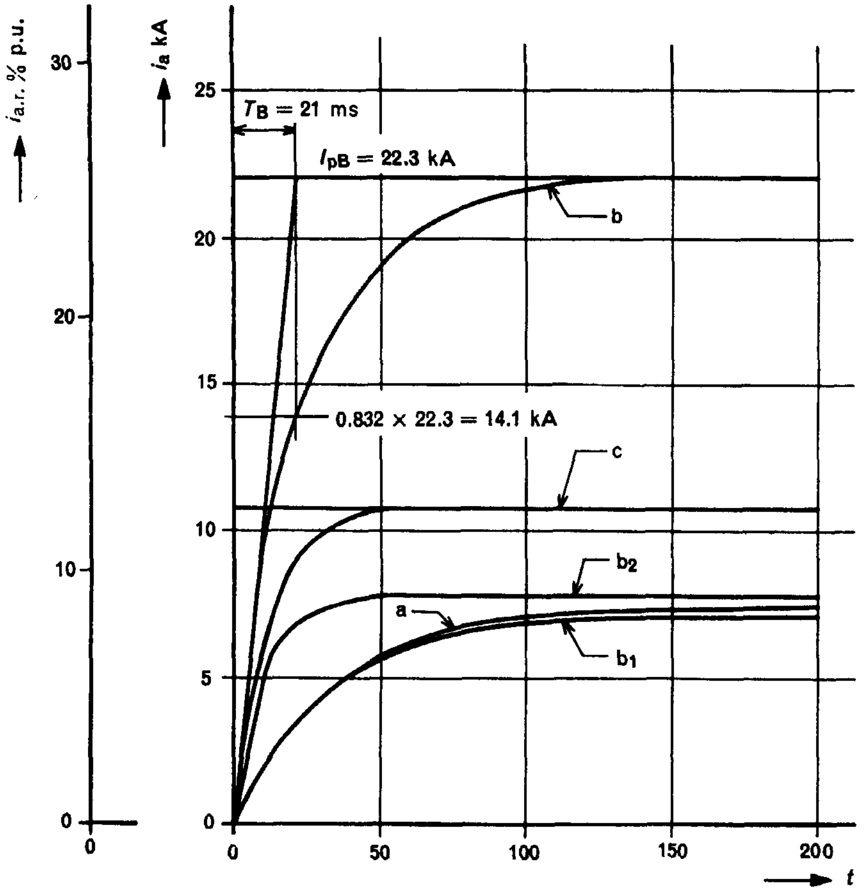


FIG. 11. — Diagram for the determination of coefficient *d*.



a = short-circuit current at the terminals of a generator (point A)

b = short-circuit current on the main switchboard busbars (point B)

b_1 = contribution of a generator

b_2 = contribution of motors

c = short-circuit current on the busbars of a sub-switchboard

12. — Characteristic of short-circuit currents at the various points of plant on Figure 9, page 31.

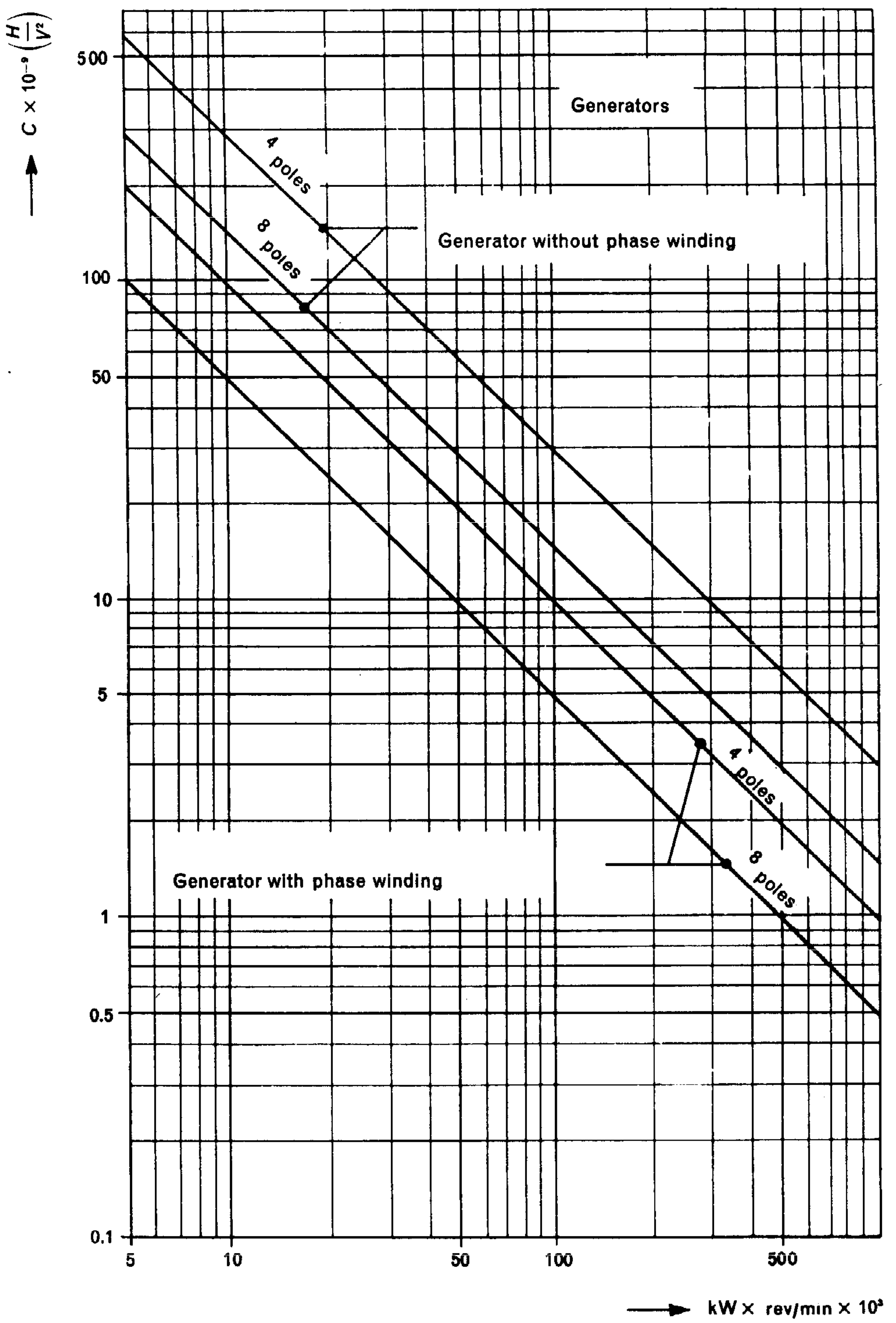


FIG. 13. — Diagram for the determination of $C = L_a/V_N^2$ for generators.

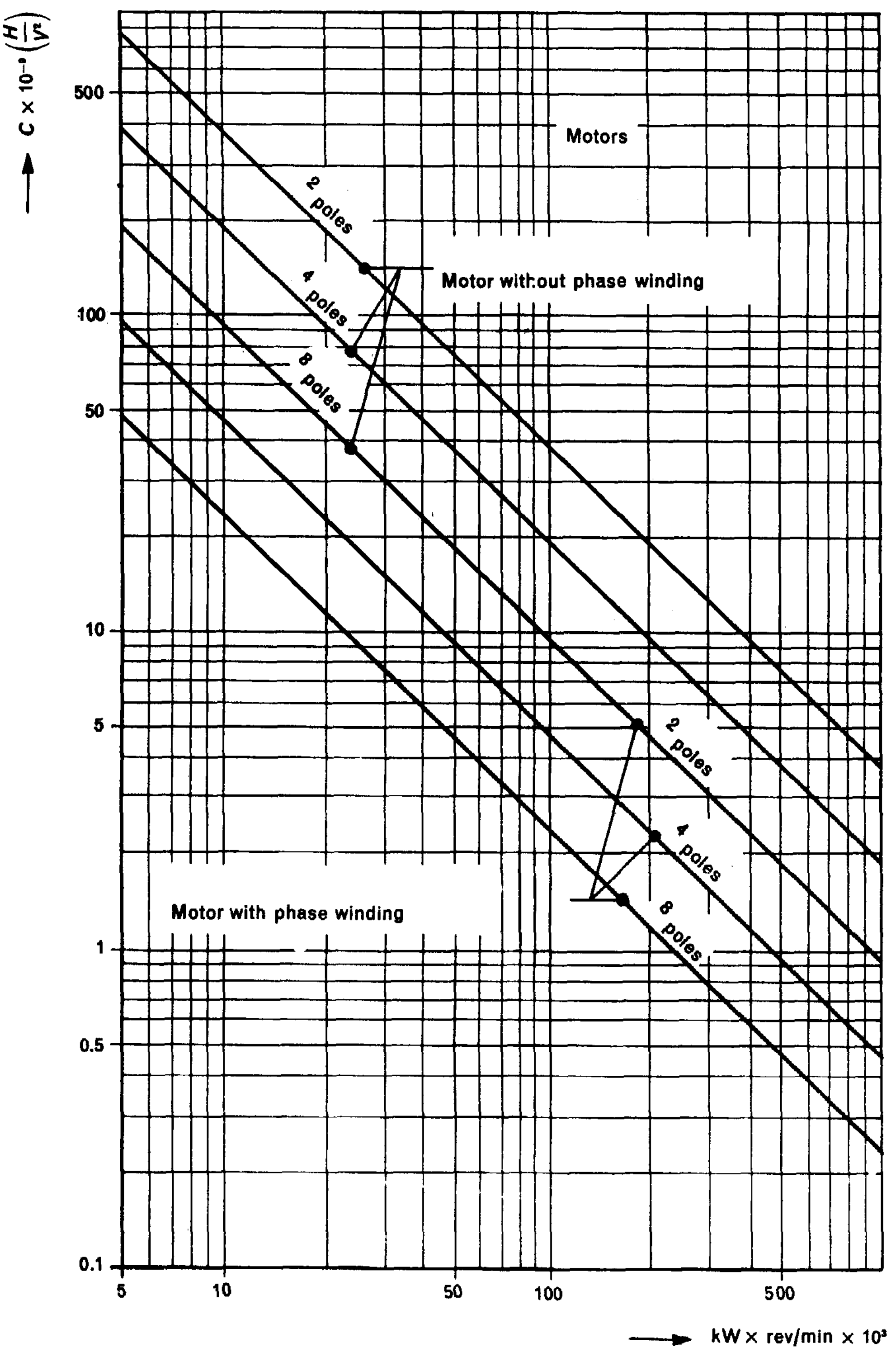


FIG. 14. — Diagram for the determination of $C = L_a/V_N^2$ for motors.

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